

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**Potential Electricity Generation from Small Scale
Solar Photovoltaic Systems -**

**Case Study 1: Solar Harvesting Potential from
roofs of Invercargill Homes**

And

**Case Study 2: Model Validation using Existing
Data from PV Generation on Selected New
Zealand Schools**

A thesis presented in partial fulfilment of the requirements for the
degree of

MASTER OF CONSTRUCTION

School of Engineering and Advanced Technology

At Massey University, Albany,

New Zealand

SAMANANT SAKDISETH

2015

ABSTRACT

Solar energy is abundant, free and non-polluting. Solar energy can offset the consumption of fossil fuels, greenhouse gas emission reduction targets and contribute to meeting the fast-growing energy demands. The use of solar energy for electricity generation from photovoltaic (PV) panels has increased but is still not a widely utilised technology in New Zealand. This research approximated the potential solar energy that could be harvested from the rooftops of existing residential buildings in a case study city.

This research is divided into two work strands, each involving a case study. The first strand investigated if a model could be developed, using existing data sources to determine the solar harvesting potential from the rooftops of existing residential buildings. The second strand involved the validation of the solar PV prediction model proposed in the first strand of the research, to test the reliability of the modelling outcomes.

Invercargill City was selected as the study city for case study 1. Invercargill is the southernmost city in New Zealand so represents a worst case scenario. The method involved merging computer-simulation of solar energy produced from PV modelling and mapping incoming solar radiation data from north facing residential rooftop area. The work utilised New Zealand statistical census map of population and dwelling data, as well as digital aerial map to quantify the efficient roof surface area available for PV installations. The solar PV potential was calculated using existing formulas to investigate the contribution of roof area to the solar PV potential in buildings using roof area and population relationship.

The estimated solar PV potential was 82,947,315 kWh per year generated from the total solar efficient roof surface area of 740,504 m². This equates to approximately 60.8% of the residential electricity used in Invercargill's urban

area, based on the 7,700 kWh typical annual electricity consumptions per household. The result represents an immense opportunity to harvest sustainable energy from Invercargill's residential rooftops.

To verify the accuracy of the developed method for predicting the PV outputs, the model was applied to actual generation data from grid-connected solar photovoltaic (PV) systems that are installed in New Zealand schools under the Schoolgen programme (Case Study 2). A total of 66 Schoolgen PV rooftop models were incorporated in the analysis. At this stage, the actual system parameters including size, panel type and efficiency were included in the analysis. The performance prediction and analysis outcome showed the parameters and operating conditions that affect the amount of energy generated by the PV systems. This part of the research showed the area where the PV model can be improved.

The predicted generation from the model was found to be lower than the actual generation data. Schoolgen systems operating at over 0.75 performance ratio were found to be underestimated. This indicated that most Schoolgen PV systems were operating at higher capacities than predicted by the default value of system losses. The analysis demonstrated the effects of PV technology type, site orientation, direction and tilted angle of the panels on the ability to generate expected amount of potential capacity based on solar resource availability in different site scenarios. This in turn has provided more in depth analysis of the research and served to expand the area for improvements in the design of the model.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude and appreciation to my chief supervisor, Professor Robyn Phipps, for her constant advice and guidance, with generous support and encouragement from the beginning through to the completion of this thesis.

I would also like to thank my co-supervisor, Professor Jasper Mbachu, for the time and effort discussing research topics and direction.

I am grateful to the love and support of my family. Their patience and kind understanding have truly contributed in making this study possible.

TABLE OF CONTENTS

ABSTRACT	i
ACKNOWLEDGEMENT	iii
TABLE OF CONTENTS	iv
LIST OF FIGURES	ix
LIST OF TABLES	xii
LIST OF EQUATIONS	xiv
ABBREVIATIONS	xv
CHAPTER 1: INTRODUCTION	1
1.1 Purpose	1
1.2 The Need for the Research	2
1.3 Research Objectives	5
1.3.1 Case Study 1 – Solar Harvesting Potential from Roofs of Invercargill Homes	5
1.3.2 Case study 2 – Model Validation Using Existing Data from PV Generation on Selected New Zealand Schools	6
1.4 Limitations of the Research	7
1.5 Structure of the Thesis	7
CHAPTER 2: LITERATURE REVIEW	9
2.1 Background	9
2.1.1 Trends in Renewable Electricity in the Global Context: A Key Strategy to Energy Crisis and Climate Change	9
2.1.2 New Zealand Electricity and Solar PV Potential	13
2.1.3 Current Status of PV Deployment in New Zealand	16
2.1.3.1 Residential Household Sector	16
2.1.3.2 Solar Electricity for New Zealand Schools	17

2.2 Review of PV Technologies and Developments.....	19
2.2.1 Solar Photovoltaic System and Components	19
2.2.2 PV Cell Technologies	21
2.2.2.1 First Generation Cells - Crystalline Silicon (c-Si).....	21
2.2.2.2 Second Generation Cells - Thin Film	22
2.2.2.3 Third Generation Cells - Emerging Photovoltaics.....	23
2.3 Factors Affecting the Operation and Efficiency of PV Electricity Generation System.....	24
2.3.1 Solar Radiation.....	24
2.3.2 Module Orientation, Shading and Sun Angle	25
2.3.3 Effects of PV Technology Types	26
2.3.4 Effects of Ambient Temperature	27
2.3.5 Effects of System Equipment.....	29
2.4 Economics and Applications of Grid-Connected PV System.....	30
2.5 Urban-Scale Solar Mapping Projects in New Zealand	33
2.5.1 Auckland Solar Mapping Projects	34
2.5.2 Solar PV Potential for Each Region in New Zealand	35
2.6 Modelling Solar Radiation	36
2.6.1 Solar Radiation Components	36
2.6.1.1 Factors Affecting Solar Radiation	37
2.6.2 Solar Radiation Modelling: Existing Approaches	38
2.6.3 Tools for Solar Radiation Modelling in Urban Environment	40
2.6.3.1 Modelling Based on the DEM and GIS	41
2.6.3.2 3D Solar Evaluation - Computer-Based Daylighting Simulations	43
2.7 Calculating Rooftop Area	45
2.8 Calculating PV Potential from Rooftop	47
2.8.1 Solar Efficient Roof Area	47

4.4.1 Review of the Methodology and Findings.....	98
4.4.2 Reliability of the Outcome, Model Limitations and Potential Uncertainties.....	100
4.4.3 Implications for Future Analysis	102
CASE STUDY 2 – MODEL VALIDATION USING EXISTING DATA FROM PV GENERATION ON SELECTED NEW ZEALAND SCHOOLS	
CHAPTER 5: MODEL VALIDATION.....	104
5.1 Description of the Case Study	104
5.1.1 About Schoolgen Programme	104
5.1.2 Description of Schoolgen PV Systems	106
5.1.3 Electricity Generation Data.....	108
5.2 Model Validation Methods	111
5.2.1 Schoolgen Selection and System Installation Data.....	115
5.2.2 Digitising School Buildings with Roof-Mounted PV Panels	117
5.2.3 Solar Access Analysis.....	118
5.2.4 Global Formula for Calculating PV Potential	121
5.2.5 Data Analysis	122
5.2.5.1 Comparison of Modelled Findings with Actual Generation..	122
5.2.5.2 Comparing Schoolgen System Performance	122
CHAPTER 6: MODEL VALIDATION RESULTS	124
6.1 Solar Modelling Results	124
6.2 Calculating Schoolgen PV Potential Generation	128
6.3 Comparison of Modelled Findings with Actual Generation.....	131
6.4 Comparing Schoolgen Systems by Capacity Factor	135
6.5 Schoolgen PV Analysis - Findings and Discussion	139
6.5.1 Modelling Solar Radiation.....	139
6.5.2 PV Performance Prediction	141
6.5.3 Performance Ratio	142

6.5.4 Schoolgen Performance Indication from Capacity Factor.....	145
CHAPTER 7: CONCLUSIONS	147
7.1 Case Study 1 - Solar Harvesting Potential from Roofs of Invercargill Homes	147
7.2 Case study 2 – Model Validation Using Existing Data from PV Generation on Selected New Zealand Schools	148
7.3 Recommendations for Future Work.....	150
REFERENCES.....	152

LIST OF FIGURES

Figure 2-1: Renewable energy share of global final consumption in 2010 (Source: REN21, 2012, p.21)	11
Figure 2-2: Renewable energy share of global final energy consumption in 2012 (Source: REN21, 2014, p.25).....	12
Figure 2-3: Average annual growth rates of renewable capacity 2006-2011 (Source: REN21, 2012, p.22).....	13
Figure 2-4: New Zealand annual electricity generation by fuel type (Source: MBIE, 2014b, p.56)	14
Figure 2-5: The possible components of a photovoltaic system (Source: Wikipedia, 2015a)	19
Figure 2-6: Illustrations of a typical grid-connected PV system with a power conditioning unit and connections to utility grid in comparison to a stand-alone off-grid system consisting of a battery system (Source: Solar Energy Technologies Programme, 2005)	20
Figure 2-7: Relationship of PV module efficiency and PV module temperature (Source: Yamaguchi et al, 2003 in Meral & Dincer, 2011)	28
Figure 2-8: The price of a standard 3kW solar power system in New Zealand (Source: My Solar Quotes Limited, 2015)	31
Figure 3-1: Study area - Invercargill City Residential Zone within the Invercargill District Plan's Urban Boundary (Source: Corson Consultancy, 2010, p.14)	53
Figure 3-2: Invercargill housing styles (Source: Corson Consultancy, 2010, p.20)	54
Figure 3-3: Climate data for Invercargill (source: NIWA, 2013, as cited in Wikipedia, 2014).....	56
Figure 3-4: New Zealand mean annual sunshine hours (source: NIWA, 2013) ..	56
Figure 3-5: Solar Radiation in New Zealand (source: NIWA, 2005)	57

Figure 3-6: Monthly averaged daily global irradiance comparing Invercargill to other New Zealand locations (source: EECA, 2001, p. 14).....	58
Figure 3-7: Rooftop PVGen Model for calculating rooftop PV potential for Case Study 1	60
Figure 3-8a: Invercargill City suburbs and boundary as defined in the geographical area unit of Statistic New Zealand census data (Source: Statistic New Zealand, 2013).....	62
Figure 3-8b: Invercargill City meshblocks in the geographical area unit representing the Statistic New Zealand census data of population and dwelling counts (Source: Statistic New Zealand, 2013)	62
Figure 3-9: Example of available Invercargill City Council’s aerial map with GIS-based data layers (Source: Invercargill City Council, 2014)	63
Figure 3-10: Example of digitized roof patterns on the sample set of buildings (Source: Invercargill City Council, 2014).....	70
Figure 3-11: Example of 3D building model of the representative samples in an area unit.....	70
Figure 3-12: Imported model of sample buildings displayed in Ecotect environment	72
Figure 3-13: Example of overshadowing on the surfaces (shading effects from the surrounding structures)	73
Figure 3-14a: Example of 2mx2m surface subdivisions applied to the building models before solar simulation	74
Figure 3-14b: Result of solar simulation on the 2mx2m surface subdivisions on rooftop.....	74
Figure 3-15a: Display of incoming solar radiation on roof surfaces	76
Figure 3-15b: Display of incoming solar radiation across the entire surfaces of the sample city blocks	76
Figure 3-16: Microsoft Excel numerical list of individual object area and total radiation received on each surface	78
Figure 5-1: Schoolgen launched (Source: Schoolgen, 2006-2015)	105

Figure 5-2: Locations of Schoolgen schools across New Zealand (Source: Schoolgen, 2006-2015)	106
Figure 5-3: Typical circuit diagram of the PV system installed at a Schoolgen school (Source: Schoolgen, 2006-2015)	107
Figure 5-4: Diagram of how the PV generation data were collected from all the Schoolgen schools (Source: Schoolgen and NZ Power Company Genesis Energy, 2006-2015)	109
Figure 5-5: Example of PV generation data of a Schoolgen school in a defined time period (Source: Schoolgen and NZ Power Company Genesis Energy, 2006-2015)	109
Figure 5-6: Example of a Schoolgen school's PV system details (Source: Schoolgen and NZ Power Company Genesis Energy, 2006-2015)	111
Figure 5-7: Rooftop PVGen Model for calculating rooftop PV potential for Case Study 2	114
Figure 5-8: Examples of 3D-modeled school building with roof-mounted PV panels digitized in 3D-CAD software (#55 Amesbury School – Wellington City and #34 Aokautere School – Palmerston North)	118
Figure 5-9a: Display of Ecotect analysis for incoming solar radiation on PV panels (#55 Amesbury School – Wellington City)	120
Figure 5-9b: Microsoft Excel numerical list of individual object area and total radiation received on each surface (Example from #55 Amesbury School – Wellington City)	120
Figure 6-1: Map of New Zealand NIWA climate zones and weather stations utilized by the solar analysis function of Ecotect software (Source: Autodesk Ecotect Software)	127
Figure 6-2: Frequency counts of occurrences by the number of estimations that fell within each interval size of percentage errors	134

LIST OF TABLES

Table 3-1: Sample design for digitization	67
Table 3-2: New Zealand house typologies summary (source: Ryan et al, 2008) .	69
Table 3-3: Summary of input parameters for Invercargill City solar access analysis settings in Ecotect	75
Table 3-4: Summary of output data obtained from Ecotect simulation by each suburb samples	78
Table 3-5: Summary of related variables for calculating solar PV potential by the proposed equation	82
Table 4-1: Summary of results – Gross rooftop surface area for total roof area per person	84
Table 4-2: Summary of modelling results – Distribution of solar efficient roof area	86
Table 4-3: Calculation of solar PV energy potential by the proposed equation: Energy output/person = (PR x Me) x Annual average solar radiation x (% of solar efficient roof area x total roof area/person), PR = 0.75, Me = 0.12	93
Table 4-4: Extrapolation of roof surface data to total residential occupied dwellings in the study area	96
Table 4-5: Summary of obtained data as indicators for potential implications on the whole context	97
Table 5-1a: List of Schoolgen schools for digitization (2kW capacity installations)	116
Table 5-1b: List of Schoolgen schools for digitization (4kW capacity installations)	117
Table 5-2: Summary of input parameters for Schoolgen solar access analysis settings in Ecotect	119

Table 6-1a: Summary of solar modelling results of Schoolgen schools (2kW capacity installations)	125
Table 6-1b: Summary of solar modelling results of Schoolgen schools (4kW capacity installations)	126
Table 6-2a (List of 2kW capacity installations): Calculation of PV generation potential by the proposed equation: Energy output (E) = Total panel area (A) x modelled annual average solar radiation (H) x Module Efficiency (r) x Performance Ratio (Pr)	129
Table 6-2b (List of 4kW capacity installations): Calculation of PV generation potential by the proposed equation: Energy output (E) = Total panel area (A) x modelled annual average solar radiation (H) x Module Efficiency (r) x Performance Ratio (Pr)	130
Table 6-3a: Comparison of the modelled prediction with actual PV generation from Schoolgen data for 2kW capacity installations	132
Table 6-3b: Comparison of the modelled prediction with actual PV generation from Schoolgen data for 4kW capacity installations	133
Table 6-4a: Capacity factor calculated for each Schoolgen schools for 2kW capacity installations	136
Table 6-4b: Capacity factor calculated for each Schoolgen schools for 4kW capacity installations	137
Table 6-5a: The calculation to determine the value of the performance ratio on the basis of modelled solar radiation to meet the actual production level of Schoolgen systems for 2kW installations	143
Table 6-5b: The calculation to determine the value of the performance ratio on the basis of modelled solar radiation to meet the actual production level of Schoolgen systems for 4kW installations	144

LIST OF EQUATIONS

Equation 1: Wiginton et al. (2010)’s annual energy output calculation.....	50
Equation 2: Amago & Poggi (2014)’s annual PV energy calculation	50
Equation 3: Global PV Formula by Photovoltaic-software (2014).....	79
Equation 4: Mackay’s approach (MacKay, 2009 in Eltayeb 2013) to PV calculation	80
Equation 5: Proposed equation for PV calculation	81
Equation 6: Percentage Error Formula.....	122
Equation 7: Capacity Factor Formula	123

ABBREVIATIONS

AC:	Alternating Current electricity
BIPV:	Building Integrated Photovoltaics
BOS:	Balance of System
CAD:	Computer Aided Design
COP:	Coefficient of Performance
DC:	Direct Current electricity
DEM:	Digital Elevation Model
DHI:	Diffuse Horizontal Irradiance
DNI:	Direct Normal Irradiance
FIT:	Feed-in Tariff
GIS:	Geographic Information System
GHI:	Global Horizontal Irradiance
GW:	Gigawatts (10^9 Watts)
GWh:	Gigawatt-hour
HEEP:	Household Energy End-use Project
kW:	Kilowatt (10^3 Watts)
kWh:	Kilowatt-hour
kWp:	Kilowatt-peak
LCOE:	Levelized cost of electricity
LiDAR:	Light Detection and Ranging technology
MJ:	Megajoule (10^7 Joules)
MPP:	Maximum Power Point
MPPT:	Maximum Power Point Tracking
MWh:	Megawatt-hour (10^7 Watt-hours)
OECD:	The Organisation for Economic Co-operation and Development
PV:	Photovoltaics
PJ:	Petajoule (10^{15} Joules)
RPS:	Renewable Portfolio Standards
SVF:	Sky View Factor
UHI:	Urban heat island

